# Extraction of $^{229}$Th$^{3+,2+}$ using RF carpet gas cell and observation of internal conversion process of $^{229m}$Th

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The first excited state of the $^{229}$Th nucleus, $^{229m}$Th, has an excitation energy of ∼8.3 eV,[1,2)] which may lead to variations in the decay modes (internal conversion (IC), electronic bridge (EB) transitions, and $\gamma$-ray emission) depending on the chemical environment. To observe the EB transitions and $\gamma$-ray emission of $^{229m}$Th, we are aiming to trap $^{229m}$Th ions such as $^{229m}$Th$^{3+}$, $^{229m}$Th$^{2+}$, $^{229m}$Th$^{+}$, and $^{229m}$Th molecular ions in an ion trap.[3)] We previously developed a radiofrequency (RF) carpet gas cell and extracted $^{220}$Rn ions emitted from an $^{224}$Ra source.[3)] In this study, we fabricated an ion trap and then extracted and trapped $^{229}$Th ions produced from a $^{233}$U source. Moreover, we confirmed the existence of the IC decay of $^{229m}$Th using $^{229}$Th ion bunches created by the ion trap, which was reported only by the Munich group.[4,5)]

We fabricated a quadrupole ion trap having three segments (Trap 1, 2, and 3), and it was connected between the quadrupole ion guide (QPIG) and the quadrupole mass separator (QMS), as shown in Fig. 1. Gasses can be introduced into the ion-trap region for changing the chemical state of $^{229m}$Th ions. Trap 1 has four T-shaped electrodes called LINAC rods,[6)] which make axial gradient to rapidly move ions downstream in the presence of gas.

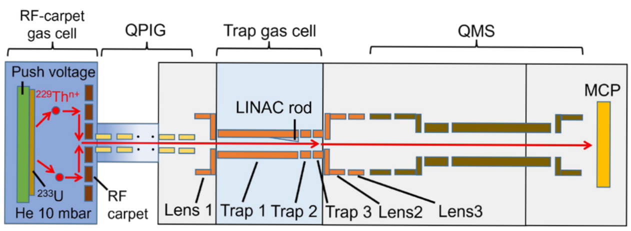


Fig. 1. Schematic view of the ion trap connected with the RF-carpet gas cell and the QMS.

We placed a $^{233}$U source (diameter 90 mm, 596(10) kBq) inside the RF-carpet gas cell. The gas cell was first evacuated to less than $1 \times 10^{-7}$ Pa by a getter pump, and then filled with purified He gas of 10 mbar. $^{229}$Th ions recoiling out of the $^{233}$U source were decelerated by the gas and transported by DC and RF voltages to the ion trap. First, we continuously extracted ions by operating the ion trap as an ion guide and detected them with a multichannel plate detector (MCP). As shown in Fig. 2, we successfully

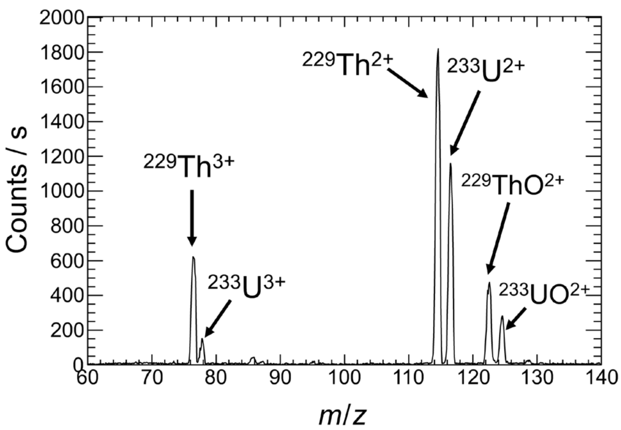


Fig. 2. Mass spectrum of ions extracted to the MCP.

extracted $^{229}$Th$^{3+}$ and $^{229}$Th$^{2+}$ using the RF-carpet gas cell, having simpler electronics and a smaller chamber size than the RF-funnel gas cell developed by the Munich group.[4)]

We made short ion bunches using the ion trap for observing the IC electrons of $^{229m}$Th. First, the ions were trapped in Trap 3 by applying +10 V to Lens 2 (Fig. 1) at a He pressure of 0.5 Pa. They were collisionally cooled for 20 ms and then extracted downstream by switching the voltage of Lens 2 to −35 V. Each ion bunch had ∼270 $^{229g,\,m}$Th$^{3+}$ (∼5 $^{229m}$Th$^{3+}$), and ∼80 $^{233}$U$^{3+}$ ions. The ion bunches were repeatedly extracted to the MCP by two different MCP surface voltages of −2000 and −50 V to detect only ions and both ions and IC electrons, respectively. Figure 3 shows the time traces of the MCP counts. For $^{229}$Th$^{3+}$, the decay curve for −50 V is clearly different from that for −2000 V, while no such difference is observed for $^{233}$U$^{3+}$. The shapes of ion bunches at

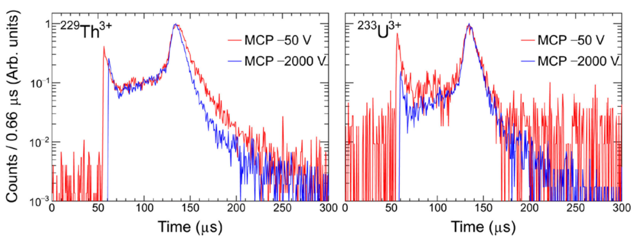


Fig. 3. MCP counts as a function of the time at MCP surface voltages of −50 V (red) and −2000 V (blue) for $^{229}$Th$^{3+}$ (left) and $^{233}$U$^{3+}$ (right). The plots are arranged so that the peak tops at 134 $\mu$s are matched to each other.

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$-2000$ and $-50$ V should be the same as observed for $^{233}U^{3+}$. Hence, the decay curve having longer lifetime for $^{229}Th^{3+}$ at $-50$ V corresponds to IC electrons of $^{229m}$Th, which were emitted after the neutralization of $^{229m}Th^{3+}$ on the MCP surface.[4] The preliminary value of the IC-decay half-life is 8(1) $\mu$s, which is consistent with the previous study (7(1) $\mu$s[5]). Hence, we successfully confirmed the existence of the IC decay of $^{229m}$Th.[4,5] We will introduce some reactive gasses into the ion trap to make various chemical species of $^{229m}$Th to observe the EB transitions.

References

1) B. Seiferle *et al.*, Nature **573**, 243 (2019).
2) A. Yamaguchi *et al.*, Phys. Rev. Lett. **123**, 222501 (2019).
3) Y. Shigekawa *et al.*, RIKEN Accel. Prog. Rep. **55**, 127 (2022).
4) L. von der Wense *et al.*, Nature **533**, 47 (2016).
5) B. Seiferle *et al.*, Phys. Rev. Lett. **118**, 042501 (2017).
6) A. Loboda *et al.*, Eur. J. Mass Spectrom. **6**, 531 (2000).